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An *RXTE* study of M87 and the core of the Virgo cluster

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ABSTRACT

We present hard X-ray observations of the nearby radio galaxy M87 and the core of the Virgo cluster using the *Rossi X-ray Timing Explorer*. These are the first hard X-ray observations of M87 not affected by contamination from the nearby Seyfert 2 galaxy NGC 4388. Thermal emission from Virgo's intracluster medium is clearly detected and has a spectrum indicative of $kT \approx 2.5$ keV plasma with approximately 25% cosmic abundances. No non-thermal (power-law) emission from M87 is detected in the hard X-ray band, with fluctuations in the Cosmic X-ray Background being the limiting factor. Combining with *ROSAT* data, we infer that the X-ray spectrum of the M87 core and jet must be steep ($\Gamma_{\rm core} > 1.90$ and $\Gamma_{\rm jet} > 1.75$), and we discuss the implications of this result. In particular, these results are consistent with M87 being a mis-aligned BL-Lac object.

1. Introduction

The nearest giant elliptical galaxy, M87 (NGC 4486), holds a central place in the study of low-luminosity radio galaxies and extragalactic radio jets. This galaxy, situated at the center of the Virgo cluster of galaxies, is associated with the Faranoff-Riley class I radio source Virgo-A and displays the most prominent extragalactic radio jet in the northern sky. It was the first extragalactic jet to be discovered (Curtis 1918) and has since been subjected to intense observational study at all available wavelengths (see Biretta 1993 for a review). The close proximity of this source, about 16 Mpc (e.g., Tonry 1991), makes it a crucial laboratory for testing our understanding of both extragalactic jets and the central engine structure of radio-loud AGN.

In the soft X-ray band, imaging with the high-resolution imagers (HRIs) on both the *Einstein* and *ROSAT* satellites have resolved emission from the core of M87 and knots A, B and D of its optical jet (Schreier, Gorenstein & Feigelson 1982; Biretta, Stern & Harris 1991; hereafter BSH91). The mechanisms underlying any of these emission components is unknown. Suggestions for the jet emission mechanism include synchrotron emission from ultra-relativistic ($\gamma \sim 10^7$) electrons in the jet plasma, inverse Compton scattering of infra-red/optical photons by a population of $\gamma \sim 100$ electrons in the jet plasma, and thermal bremsstrahlung from shock heated gas surrounding the jet. The observed core emissions could represent the inner jet with one of the above mechanisms producing the X-rays. On the other hand, emission from an accretion disk corona (as in the Seyfert case) or a hot accretion disk (such as an Advection Dominated Accretion Flow; Reynolds et al. 1996) might also be important for understanding the core emissions.

For years there was a mystery surrounding the hard X-ray emission from M87 and the Virgo cluster. Whereas the centroid of the low-energy emission lies on M87, Davison (1978) used *Ariel-V* data to show that the higher-energy emissions possessed a different centroid (displaced to the north-west by $\sim 1°$). This puzzle was resolved by the coded-mask imaging from *Spacelab-2* which found that the high-energy emissions (10 keV or greater) of the Virgo cluster are dominated by the Seyfert 2 galaxy NGC 4388 (Hanson et al. 1990). NGC 4388 is displaced from M87 by just over a degree to the north-west. An unambiguous measurement of the hard X-ray flux, spectrum and variability properties of M87 has proven difficult due to the presence of this confusing source. Takano & Koyama (1991) analyzed *Ginga* scanning data and determined a photon index of $\Gamma = 1.9 \pm 0.02$ and a 10–20 keV flux of $F_{10-20\,\mathrm{keV}} = 1.6 \times 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, corresponding to a 2–10 keV flux of $F_{2-10\,\mathrm{keV}} = 3.4 \times 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (assuming a simple extrapolation of the 10–20 keV powerlaw to lower energies). Hanson et al. (1990) report upper limits that are 5 times weaker. Takano & Koyama (1991) take this as evidence for variability.

With the exception of the *EXOSAT* ME which suffered from severe background subtraction issues at high energies, the *Rossi X-ray Timing Explorer (RXTE)* is the first hard X-ray observatory with a sufficiently small field of view to avoid contamination by NGC 4388. In this *letter* we report four *RXTE* observations of M87. The AGN/jet is not detected above the thermal emission of the Virgo cluster, and upper limits on its flux are given. We include the effect of unknown fluctuations in the Cosmic X-ray Background (CXB) when deriving our limits on the non-thermal emission and these, indeed, turn out to be the limiting factor for these data. Astrophysical implications of this non-detection are discussed in Section 4.

2. Observations and basic data reduction

We observed M87 with *RXTE* four times. The dates (and good on-source exposure times) were 30-Dec-1997 to 2-Jan-1998 (42600 s), 9-Jan-1998 to 12-Jan-1998 (43500 s), 19-Jan-1998 to 22-Jan-1998 (35500 s), and 30-Jan-1998 to 3-Feb-1998 (44900 s). The motivation of the project was to search for the hard X-rays from M87 and its jet, and study their spectrum and variability.

RXTE is a hard X-ray observatory possessing two pointed instruments, the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE), as well as an all-sky monitor (ASM). In this work, we use data from the PCA and HEXTE.

The PCA consists of five nearly identical co-aligned Xenon proportional counter units (PCUs) with a total effective area of about $6500\,\mathrm{cm}^2$ and is sensitive in the energy range from 2 keV to $\sim$ 60 keV (Jahoda et al. 1996). Data taken in STANDARD-2 mode were extracted into spectra and lightcurves using FTOOLS V4.1 supplemented with the *RXTE* patch (A. Smale, private communication). For spectral fitting, response matrices were generated using the FTOOLS routine PCARMF V3.3 (corrected for the 1998-Aug-29 bug in which PCARMF failed to account for temporal variations of the response matrix). To take into account the remaining uncertainties of the matrix we added 1% systematic errors to our data. This value was determined from the deviations from a pure power-law in a fit to the Crab Nebula and pulsar spectrum. Background subtraction was performed using the latest background models (released in June 1998 as part of the RXTE patch to FTOOLS V4.1). To increase signal-to-noise, only data from the top layer of the PCUs are considered here. We limit our consideration to the energy range 4–15 keV — the lower bound is determined by the lower limit of the well calibrated energies, whereas the upper bound is the energy at which the data become background dominated.

The HEXTE consists of two clusters of four NaI/CsI-phoswich scintillation counters, sensitive from 15 to 250 keV (Rothschild et al. 1998). Background subtraction is done by source-background rocking of the two clusters. No signal from M87 was detected in HEXTE for either the individual observations or the co-added data of all of our datasets. However, the limits set by these non-detections are uninteresting compared with the PCA limits that we shall address below, and hence we shall not discuss HEXTE data any further.

The total background subtracted PCA count rate was $113\,\mathrm{counts\,s^{-1}}$ for all 5 PCUs, with no evidence for variability either between the four observations or within individual observations. In the absence of any temporal structure, we focus on the spectral aspects. We have extracted 4 PCA spectra, one for each individual observation, and rebinned to at least 20 photons per energy bin. This is a requirement for the χ^2 analysis of the following section to be appropriate. Spectral fitting was then performed using the XSPEC V10.0 package.

3. Spectral results

In this section, the 4–15,keV spectra resulting from the four observations are analyzed individually in order to assess spectral variability. Since we fail to detect spectral variability, we also fit the combined spectrum jointly. We expect each spectrum to be dominated by thermal plasma emission from the ICM of the Virgo cluster. Non-thermal emission from the AGN or jet, if present, would be revealed as a hard tail above and beyond the thermal emission.

For these data, unknown fluctuations in the CXB are the limiting factor in our ability to study the non-thermal emission from M87. The spectral fitting presented in section 3.1 (and in Table 1) incorporates this uncertainty by including such fluctuations as an extra model component. In detail, we include a power-law component with photon index $\Gamma = 1.8$ which is allowed to vary in normalization (measured at 1 keV) between $N_{\rm CXB} = \pm 2 \times 10^{-4}\,\mathrm{ph\,keV^{-1}\,cm^{-2}\,s^{-1}}$ (i.e., the 1-σ fluctuations of the CXB estimated by scaling the *Ginga* results of Butcher et al. [1997] to account for the instrumental responses, effective areas and fields of view).

3.1. The thermal plasma and limits on a $\Gamma = 2$ power-law

Initially, these spectra were fitted with a single temperature thermal plasma model (Mewe, Gronenschild, & van den Oord 1985; Kaastra 1992) modified by Galactic absorption ($N_{\rm H} = 2.5 \times 10^{20}\,\mathrm{cm^{-2}}$) and redshifted appropriately for the Virgo/M87 system ($z = 0.003$). The resulting fits are acceptable ($\chi^2_\nu \sim 1.1$ for 25 degrees of freedom) and are shown in Table 1. As can be seen from Table 1, all spectra are adequately described by a $kT \approx 2.5$ keV plasma with an abundance of $Z \approx 0.26\,Z_\odot$. Extrapolating the fits in the 2–4 keV range, the total inferred 2–10 keV flux is $2.8 \times 10^{-10}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, although there may well be a cooler cluster component contributing to the cluster X-ray emission below 4 keV (e.g. Lea et al. 1982; Matsumoto et al. 1996). The corresponding 2–10 keV luminosity is $8.7 \times 10^{42}\,\mathrm{erg\,s^{-1}}$.

The results of the thermal plasma fit to all four datasets simultaneously (i.e., the combined fit) are shown in Fig 1. A 'line-like' feature can be seen at $\sim 6\,\mathrm{keV}$. This feature is seen in all PCU detectors individually and in each observing period. An additional narrow Gaussian line with energy $E = 6.22 \pm 0.12\,\mathrm{keV}$, slightly less than the cold iron fluorescent line energy of iron, and equivalent width 84 eV describes this feature well and produces a large improvement in the goodness of fit ($\chi^2_\nu = 56.0/107$). There are several reasons for suspecting that this line is *not* real. Firstly, one must be immediately suspicious since this is a weak line-feature embedded in the wings of a much stronger line (i.e., the ionized emission line from the thermal cluster gas). Secondly, such a line is not seen in *ASCA* data of the Virgo cluster (an examination of archival *ASCA* data gives an upper limit of $\sim 20\,\mathrm{eV}$ on the equivalent width of a line at these energies). Thirdly, there is no astrophysical precedent for observing such a line from a cluster dominated system. While we cannot firmly reject the hypothesis that this line is real, we suspect that it is due to a small mismodelling of the ionized emission lines. Furthermore, the presence of this line in the spectrum does not affect the best fit values or uncertainties of the other spectral parameters. Thus, we shall not discuss this feature any further, and shall not include it in the spectral fitting described below.

In order to assess the presence of hard non-thermal emission from the AGN or jet, a power-law component was added to the thermal plasma model. In no case did the addition of the power-law component lead to any significant improvement in the goodness of fit. Table 1 quotes the 90 per cent limits on the normalization of the power law (at 1 keV) assuming a photon index of $\Gamma = 2$ (close to the canonical value for Type-1 AGN).

3.2. Detailed limits on non-thermal emission

Given the lack of any spectral variability, we choose to refine our limits on the non-thermal emission using the combined spectrum (i.e., summing the spectra from our individual observations). Here, we compute confidence contours on the $(\Gamma, N_{\rm pow})$-plane using a more rigorous treatment of the effect of CXB fluctuations on our spectral fitting.

Since we know the probability distribution of the CXB fluctuations (Butcher et al. 1997), we can integrate over possible fluctuations and obtain 'averaged' confidence contours. We define a likelihood function given a particular CXB fluctuation,

$$\mathcal{L}(\Gamma, N_{\rm pow}|N_{\rm CXB}) \propto \exp\left(-\frac{\chi^2(\Gamma, N_{\rm pow}|N_{\rm CXB})}{2}\right), \tag{1}$$

where $\chi^2(\Gamma, N_{\rm pow}|N_{\rm CXB})$ is derived from fitting the spectral model of the previous section to the combined data with $\Gamma, N_{\rm pow}$ and $N_{\rm CXB}$ fixed at given values. Defining the probability of a given CXB fluctuation as $p(N_{\rm CXB})$, we can belong to the HBL catagory. Thus, our data are entirely consistent with the suggestion that M87 is a misaligned HBL.

5. Conclusions

We have presented four *RXTE* observations of M87 spread over the month of Jan-1998 and totaling approximately 167 ksec of on-source exposure time. Thermal plasma emission from the Virgo cluster ICM is clearly detected in the PCA with a temperature of $kT \approx 2.5\,keV$. The metal abundance of the plasma is inferred to be $Z \approx 0.26\,Z_{\odot}$, although this must be treated as an average abundance given the known abundance gradients in this system (Matsumoto et al. 1996). There was no detection in the HEXTE.

Once the thermal ICM emission has been modeled, there is no detection of any hard X-ray non-thermal (power-law) emission in the PCA spectrum. Our upper limit on the flux of a $\Gamma = 2$ power-law component is $F_{\rm pow} < 4.1 \times 10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$. Fluctuations in the CXB are the limiting factor in our ability to set upper limits on the non-thermal emission. If the core and jet sources detected by *ROSAT* possess a power-law spectrum into the *RXTE* band, the photon indices of this sources must be $\Gamma_{\rm core} > 1.90$ and $\Gamma_{\rm jet} > 1.75$ respectively. This is entirely consistent with the hypothesis that M87 is a misaligned HBL.

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4. Discussion

Our upper limit on the hard X-ray power-law component of M87 are the most stringent to date. They are superior to the upper limits derived from *Spacelab-2* data [$F_{\rm pow}(2-10\,{\rm keV}) < 8\times10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$; Hanson et al. 1990] and *ASCA* data [$F_{\rm pow}(2-10\,{\rm keV}) < 8\times10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$; Reynolds et al. 1996]. Note that Matsumoto et al. (1996) claim a detection of the M87 power-law with $F_{\rm pow}(2-10\,{\rm keV}) \approx 8\times10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$ using the same *ASCA* data as Reynolds et al. (1996). However, the complex structure of the thermal ICM, which possesses temperature and abundance gradients as well as a possible multiphase structure, makes the thermal ICM spectrum difficult to model and so renders such conclusions about superposed non-thermal emission open to suspicion. Our limits are also inconsistent with the value of $F_{\rm pow}(2-10\,{\rm keV}) \approx 3.4\times10^{-11}\,{\rm erg\,cm^{-2}\,s^{-1}}$ derived from *Ginga* scanning data (Tanako & Koyama 1991). While this may be evidence for variability, it is also possible that scattered flux from NGC 4388 coupled with the complex thermal ICM influences the subtle analysis of Tanako & Koyama (1991). In summary, we would argue that there has never been an irrefutable detection of a hard X-ray power-law from M87.

However, both the *Einstein* and *ROSAT* HRIs have imaged variable soft X-ray point sources coincident with the core of M87 and knot-A (Schreier, Gorenstein & Feigelson 1982; BSH91; Harris, Biretta & Junor 1998; hereafter HBJ98). The last *ROSAT* measurement shown by HBJ98 was taken on 5-Jan-1998 and hence lies within these *RXTE* observations. Assuming a single (absorbed) power-law form extending from the *ROSAT* band into the *RXTE* band, the 1998 *ROSAT* fluxes can be converted into loci on the Γ-$N_{\rm pow}$ plane, as shown in Fig. 2. It can be seen that the *ROSAT* sources must possess a fairly steep high-energy spectrum ($\Gamma \gtrsim 1.90$ and $\Gamma \gtrsim 1.75$ for the core and jet respectively) in order to avoid detection by *RXTE*. If the core and jet components have the same hard X-ray spectrum, then the spectral slope must exceed $\Gamma > 2.05$ in order for the combined hard X-rays from these two sources to remain undetected. If there is significant intrinsic absorption in this system, even steeper intrinsic spectra are required.

It is informative to compare these limits with the photon indices found in various classes of AGN. In a recent *ASCA* study, Reeves et al. (1997) found that radio-loud quasars possess *ASCA* band photon indices of $\Gamma = 1.63\pm0.04$ (see also studies by Lawson et al. 1992, and Williams et al. 1992). Our data rule out the possibility that the *ROSAT* source seen in the core of M87 possesses such a flat X-ray spectrum when extrapolated to the *RXTE* band. However, Tsvetanov et al. (1998) have recently suggested that M87 is a misaligned example of a BL-Lac object. These AGN typically possess steep *ASCA*-band X-ray spectra with $\Gamma\sim1.8$ for the low-energy peaked BL-Lacs (LBL) and $\Gamma\sim2-3$ for the high-energy peaked BL-Lacs (HBL; e.g. Kubo et al. 1998). The lack of an observed break in the optical-UV spectrum of the jet (Tsvetanov et al. 1998), and the steep X-ray spectral index, would suggest that it

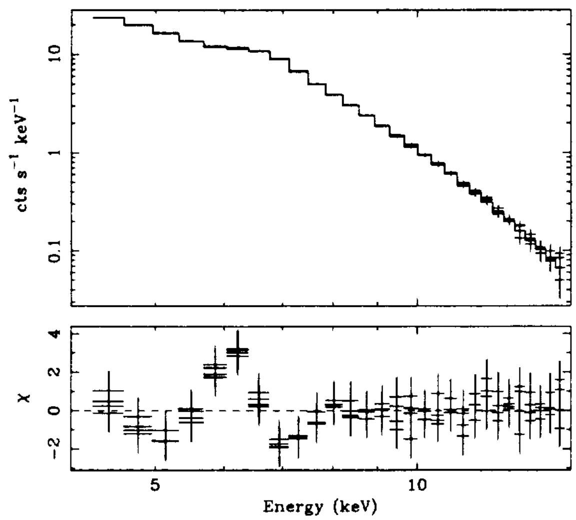

Fig. 1.— The best fitting two-component thermal fit to the combined PCA data.

Model & model parameters	Interval 1	Interval 2	Interval 3	Interval 4	combined
NH+MEKA+BACK					
kT (keV)	$2.57^{+0.14}_{-0.15}$	2.56 ± 0.03	$2.54^{+0.03}_{-0.04}$	$2.54^{+0.02}_{-0.03}$	$2.54^{+0.02}_{-0.01}$
Z ($Z_\odot$)	$0.26^{+0.01}_{-0.02}$	$0.26^{+0.02}_{-0.01}$	0.26 ± 0.02	$0.26^{+0.02}_{-0.01}$	0.26 ± 0.01
N (photons s^{-1} cm^{-2} keV^{-1} @ 1keV)	$0.62^{+0.01}_{-0.02}$	$0.62^{+0.01}_{-0.02}$	$0.63^{+0.02}_{-0.01}$	0.63 ± 0.02	0.63 ± 0.01
χ^2/dof	28.6/25	27.4/25	27.4/25	27.2/25	120/109
NH+MEKA+PO+BACK					
$N_{\rm pow}$ (10^{-3} photons s^{-1} cm^{-2} keV^{-1} @ 1keV)	< 1.8	$0.9^{-0.4}_{+1.0}$	< 1.2	< 1.9	< 1.2
$F_{\rm pow}(2-10\,{\rm keV})$ (10^{-12} erg cm^{-2} s^{-1})	< 4.6	$< 2.3^{+2.6}_{-1.0}$	< 3.1	< 4.6	< 3.1
χ^2/dof	27.2/24	24.1/24	27.3/24	26.6/24	118/108

Table 1: Spectral fits to *RXTE*-PCA data in 4–15 keV range. $N_{\rm pow}$ and N are the normalizations of the power-law component and the thermal component, respectively, at 1 keV. The power-law is assumed to have a photon index of $\Gamma = 2$ in these fits. All errors are quoted at the 90 per cent confidence level for one interesting parameter ($\Delta\chi^2 = 2.7$).